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# Science with the Square Kilometer Array: Motivation, Key Science Projects, Standards and Assumptions

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The Square Kilometer Array (SKA) represents the next major, and natural, step in radio astronomical facilities, providing two orders of magnitude increase in collecting area over existing telescopes. In a series of meetings, starting in Groningen, the Netherlands (August 2002) and culminating in a 'science retreat' in Leiden (November 2003), the SKA International Science Advisory Committee (ISAC), conceived of, and carried-out, a complete revision of the SKA science case (to appear in New Astronomy Reviews). This preface includes: (i) general introductory material, (ii) summaries of the key science programs, and (iii) a detailed listing of standards and assumptions used in the revised science case.

## 1. Process and Intent

The 1970's and 1980's saw the construction of numerous fully steerable single dish and array radio telescopes with apertures of order $10^4$ m$^2$. These telescopes allowed the study of HI 21cm emission from gas-rich galaxies in the nearby universe, e.g. out to the Virgo cluster, and, with effort, to redshift $z \sim 0.2$. In the subsequent 25 years, while optical astronomy has seen an order-of-magnitude increase in collecting area for ground-based telescopes, collecting area in radio astronomy has remained stagnant.

The idea for a 'Square Kilometer Array' (SKA) was born in the early 1990's. Such a telescope would provide two orders of magnitude increase in collecting area[1]over existing telescopes, allowing for study of the HI content of galaxies to cosmologically significant distances (i.e. to $z \sim 2$ rather than $z \sim 0.2$). The SKA project was born as an international program with the establishment by the International Union of Radio Science (URSI) in September 1993 of the Large Telescope Working Group.

The first science case for the SKA was edited by R. Taylor and R. Braun, and appeared as a publication from the Netherlands Foundation for Radio Astronomy in 1999. In August 2000, at the International Astronomical Union meeting in Manchester (UK), a Memorandum of Understanding to establish the International Square Kilometre Array Steering Committee (ISSC) was signed by representatives of eleven countries (Australia, Canada, China, Germany, India, Italy, the Netherlands, Poland, Sweden, the United Kingdom, and the United States). More information, and the current timeline, for the SKA project can be found at http://www.skatelescope.org.

The time since the publication of the Taylor-Braun document has seen a revolution in our knowledge of the local and distant Universe. We have entered an era of 'precision cosmology', where the fundamental parameters ($H_0$, $\Omega_{\rm M}$ etc) describing the emerging 'standard model' in cosmology are known to $\sim \pm 10\%$. This standard model includes 'dark energy' and 'dark matter' as the two dominant energy densities in the present-day Universe. We have probed into the time

[1]For radio telescopes (unlike optical telescopes) this leads to a two-dex increase in line, e.g. HI, sensitivity. For continuum observations, the SKA will be three-dex more sensitive than current synthesis arrays, largely because of increased bandwidth; the EVLA and e-MERLIN projects are designed to 'bridge the gap' by increasing the bandwidth of the existing VLA and MERLIN arrays.

of first light in universe, the 'epoch of reionization', when the UV emission from the first stars and (accreting) supermassive black holes reionizes the neutral intergalactic medium. Gamma-ray bursts have been shown to be the largest explosions in the universe, tracing the death of very massive stars to the earliest epochs. Supermassive black holes have gone from being a hypothetical bi-product of general relativity (GR), to being a fundamental aspect of all spheroidal galaxies and how these objects formed. Galactic 'micro-quasars', or accreting black holes of a few solar masses, have been shown to have similar properties to their supermassive cousins, but on eight orders of magnitude smaller mass scales. The recent discovery of the first known double pulsar presents the promise of the most accurate tests of strong-field GR. Extra-solar planets are now known to be a common phenomenon, and the search for terrestrial planets has begun. A new constituent of the solar system has been confirmed, the Kuiper belt objects, and these may provide the key to understanding the formation of the solar nebula. Wide-field surveys, and ultra-deep narrow-field surveys, from radio through X-ray wavelengths, have mapped out our Galaxy and the large-scale structure of the local Universe in astonishing detail.

In a series of meetings, starting in Groningen, the Netherlands (August 2002) and culminating in a 'science retreat' in Leiden (November 2003), the SKA International Science Advisory Committee (ISAC), conceived of, and carried-out, a complete revision of the SKA science case. This incorporated the newest results in astronomy, with emphasis on the most important outstanding problems. The revised science case is organized along the lines of nine science working groups (Table 1), covering all areas of modern astrophysics. The chairs of these working groups enlisted authors from a broad spectrum of the community, including theorists and multi-wavelength observers. The aim of the working groups was for completeness, with discussion of all areas in which the SKA will play a pivotal rôle in advancing our knowledge. However, the authors were instructed not to simply present review articles in radio astronomy. The resulting articles emphasize detailed analyses of topical research programs where the unique capabilities of the SKA can be exploited. These analyses employ the latest simulations and theoretical models of physical phenomena, such as cosmic reionization, galaxy formation, and star and planet formation. As such, these articles represent original research, and the book should act as an important reference for the planning of SKA 'path-finder' projects like as LOFAR and HYFAR, as well as enhancements to existing facilities like the EVLA and e-MERLIN.

## 2. Key Science Projects

In parallel with work on the science book, where the emphasis is on completeness, the ISAC has recognized a few 'Key Science Projects' (KSPs) for the SKA. These projects are defined according to three criteria: (i) ability to address important but currently unanswered questions in fundamental physics or astrophysics, (ii) science which is either unique to the radio band and the SKA, or is complementary to other wavebands, but in which the SKA plays a key rôle, and (iii) excites the broader community, and is of relevance and interest to funding agencies.

A sub-committee of the ISAC, chaired by Bryan Gaensler, was created to establish the KSPs for the SKA. Proposals were solicited from the community, and debated within the ISAC at the Geraldton SKA (August 2003) and at the Leiden science retreat (November 2003). A consensus was reached by the ISAC to put-forward five KSPs for the SKA to the International SKA Steering Committee (ISSC). These were approved by the ISSC, and appeared in February 2004 as SKA memo 44. The first five articles in this volume present each of these KSPs in detail.

- **KSP I. The Cradle of Life** There is increasing interest in astrobiology and the search for Earth-like planets. The SKA has the unique potential for studying extra-solar terrestrial planet formation, and for detecting signals from other life like us. At 20 GHz, the SKA will provide thermal imaging at 0.15-AU resolution out to a distance of 150 pc, encompassing many of the best studied Galactic star-forming regions.

Table 1
The ISAC Working Groups

| Area | Chair |
|---|---|
| The Milky Way and Local Galaxies | John Dickey (Minnesota) |
| SETI, Stellar End Products, Transient Sources | Joseph Lazio (NRL) |
| Cosmology and Large Scale Structure | Frank Briggs (ANU) |
| Galaxy Evolution | Thijs van der Hulst (Kapteyn) |
| Active Galactic Nuclei and Super Massive Black Holes | Heino Falcke (ASTRON) |
| The Life Cycle of Stars | Sean Dougherty (DRAO) |
| The Solar System and Planetary Science | Bryan Butler (NRAO) |
| The Intergalactic Medium | Luigina Feretti (IRA) |
| Spacecraft Tracking | Dayton Jones (JPL) |

Such observations will allow us to study the process of *terrestrial* planet formation, as well as studies of the evolution these proto-planetary disks on sub-AU scales on timescales of months ("movies of planet formation"). The SKA will have the capability of detecting 'leakage radiation' from extraterrestial intelligence (ETI) transmitters associated with the nearest stars, and targeted searches will involve studies of up to a million solar-type stars. Finally, the SKA will have the resolution and sensitivity to study the low order transitions of amino acids and other complex carbon biomolecules, and to follow their progress from molecular clouds to protoplanets.

- **KSP II. Strong-Field Tests of Gravity Using Pulsars and Black Holes:** Pulsar surveys with the SKA can discover tens of thousands of pulsars, amongst which there is an excellent chance of finding a pulsar in orbit around a black hole which will yield the first measurements of relativistic gravity in the ultra-strong-field limit. Thousands of millisecond pulsars will also be discovered which can form an immense 'pulsar timing array' with which gravitational waves may be detected. New probes of GR opened up will include tests of the Cosmic Censorship Conjecture and the No-Hair theorem.

- **KSP III. The Origin and Evolution of Cosmic Magnetism:** Radio astronomy is uniquely placed in its capability to study magnetic fields at large distances, through studies of Faraday rotation, polarized synchrotron emission and the Zeeman effect. The SKA could measure rotation measures for $\sim 10^8$ polarized extragalactic sources across an entire hemisphere, with an average spacing between sightlines of $\sim 60$ arcsec. The sheer weight of statistics in these data, combined with deep spectropolarimetric observations of nearby galaxies and clusters will allow a complete characterization of the evolution of magnetic fields in galaxies and clusters from redshifts $z > 3$ to the present. It will be possible to determine whether there is a connection between the formation of magnetic fields and the formation of structure in the early Universe, and to provide solid constraints on when and how the first magnetic fields in the Universe were generated.

- **KSP IV. Galaxy Evolution and Cosmology:** The original motivation for building the SKA was to detect HI in normal galaxies at high redshift, and recent developments in galaxy evolution and cosmology make this an extremely exciting prospect The SKA will provide the only means of studying the cosmic evolution of neutral Hydrogen (HI) which, alongside information on star formation from the radio continuum, is needed to understand how stars formed from gas within dark-matter over-densities. 'All hemisphere' HI redshift surveys to $z \sim 1.5$ are feasible with wide-field-of-view realisations of the SKA, and, by measuring the galaxy power spectrum in exquisite detail, will allow the first precise studies of the equation-of-state of dark energy. The SKA will be capable of other uniquely powerful cosmological studies including the measurement of the dark-matter power spectrum using weak gravitational lensing, and the precise measurement of $H_0$ using extragalactic water masers.

- **KSP V. Probing the Dark Ages:** The epoch of reionization (EoR), during which the first luminous objects in the universe formed, and then reionized the neutral IGM, can only be studied at near-IR through radio wavelengths. The SKA provides fundamental probes of the EoR in two critical areas. First, the ability of the SKA to image the neutral IGM in HI 21cm emission (and absorption) is a unique probe of the process of reionization, and is recognized as the next fundamental step in our study of the evolution of large scale structure and cosmic reionization. Second, the incomparable sensitivity of the SKA enables studies of the molecular gas, dust, and star formation activity in the first galaxies, as well as the radio continuum emission from the first accreting supermassive black holes.

An important aspect of defining KSPs is their impact on SKA array specification and design. Table 2 summarizes the SKA design specifications dictated by the the current[2]KSPs. Each of the main SKA specifications can be traced-back to one or more of the KSP requirements. This table is discussed at length in SKA memo 44.

There was a long debate within the ISAC concerning whether or not 'Exploration of the Unknown' constituted a sixth KSP. This volume ends with a detailed discussion of this topic.

## 3. Standards and Assumptions

A critical aspect of a work such as this is to establish strict telescope parameters which all authors adopt in their scientific calculations. In August 2003 the SKA project office appointed Dayton Jones to codify and rationalize the SKA specifications, in consultation with the ISAC and the Engineering Management Team (EMT). The results are shown below (see SKA memo 45). All the science articles adopt these specifications as nominal. The authors were also asked to point out areas where small changes to these specifications could lead to substantial improvements in the science delivered.

- Frequency range: 100 MHz - 25 GHz Goal: 60 MHz - 35 GHz
- Simultaneous independent observing bands: 2 pairs (2 polarizations at each of two independent frequencies, with same FoV centers)
- Maximum frequency separation of observing bands: Factor of 3 between observing band center frequencies (same FoV centers)
- Instantaneous bandwidth of each observing band: Full width = 25% of observing band center frequency, up to a maximum of 4 GHz BW for all frequencies above 16 GHz
- Sensitivity at 45 degrees elevation ($A_{\rm eff}/T_{\rm sys}$ in units of m$^2$/K): (Goal: 2500 at 60 MHz) 5000 at 200 MHz, 20000 between 0.5 and 5 GHz, 15000 at 15 GHz, and 10000 at 25 GHz (Goal: 5000 at 35 GHz) (see Table 3 for dual polarization sensitivities).
- Configuration: Minimum baselines 20 meters, 20% of total collecting area within 1

[2]Both the KSPs and their SKA design implications need to be continuously scrutinised to ensure that the SKA is positioned to deliver the best possible science; an example of a possible modification to the implied specifications for the Galaxy Evolution and Cosmology KSP is given as a footnote to Table 2.

[3]It is plausible that a precise measurement of $H_0$ via SKA observations of extragalactic water masers might prove a key experiment in early-21$^{\rm st}$-century cosmology, requiring an SKA that works up to $\sim$ 22 GHz with high line-sensitivity on intercontinental baselines.

Table 2
SKA specifications implied by Key Science Project goals.

| Topic | $A_{\rm eff}/T_{\rm sys}$ ($\rm m^2\ K^{-1}$) | Frequencies (GHz) | Max Baseline (km) | Special |
|---|---|---|---|---|
| Gravity | 20 000 at 1.4 GHz<br>timing array | 0.5–15<br>Galactic Center | 3000<br>astrometry | multifielding desirable? (TBD);<br>significant central core |
| Dark Ages | 10 000 at 0.1 MHz & 20 GHz<br>CO emission at $z > 6$ (M 82)<br>HI structure at $6 < z < 13$ | 0.1–20 | 3000<br>HI absorption<br>SMBH studies | 35 GHz for CO studies;<br>central core for HI;<br>full FOV imaging at 1.4 GHz |
| Magnetism | 20 000 at 1.4 GHz<br>RM grid | 0.3–10<br>large RMs | 300<br>confusion-limited<br>imaging at 1.4 GHz | –40 dB polarizationn purity;<br>central core;<br>full FOV imaging at 1.4 GHz |
| Cradle of Life | 10 000 at 20 GHz<br>10 K rms at 1 mas<br>in 100 hrs | $\geq 20$<br>terrestrial planet<br>formation | 3000<br>0.15 AU at 150 pc<br>at 20 GHz | 100 pencil beams within<br>FOV for targeted searches;<br>central core |
| Evolution & LSS | 20 000 at 1.4 GHz<br>$\rm M_*$ galaxy at $z = 2$ | 0.3–1.4[3]<br>galaxies to $z = 4$ | 300 | dedicated beam with FOV of<br>200 $\rm deg^2$ at 0.7 GHz is highly<br>desirable to increase survey speed |

km diameter, 50% of total collecting area within 5 km diameter, 75% of total collecting area within 150 km diameter, maximum baselines at least 3000 km from array core (angular resolution < 0.02 / f GHz arcsec)

- Image quality: Dynamic range $> 10^6$ and image fidelity $> 10^4$ between 0.5 and 25 GHz, over a range of 90 degrees in declination and 100 in angular resolution

- Contiguous imaging field of view (FoV): 1 square degree within half power points at 1.4 GHz, scaling as wavelength squared, goal: 200 square degree field of view within half power points at 0.7 GHz, scaling as wavelength squared between 0.5-1.0 GHz

- Number of separated fields of view: 1 with full sensitivity. Goal: 4 with full sensitivity. 10 simultaneous sub-arrays

- Correlator and post-correlation processing: Input bandwidth 25% of center frequency for frequencies below 16 GHz and 4 GHz for frequencies above 16 GHz (per observing band). Imaging of 1 square degree at 1.4 GHz with 0.1 arcsec angular resolution. Imaging of 200 sq. degrees at 0.7 GHz with 0.2 arcsec angular resolution. Imaging of $10^4$ separate regions within the FoV, each covering at least $10^5$ beam areas at full (maximum baseline) angular resolution. Spectral resolution of $10^4$ channels per observing band per baseline. Minimum sampling interval 0.1 ms for wide-field pulsar searches

- Beamformer capability: 50 simultaneous summed (phased array) beams within FoV, inner 5 km diameter of array. No time averaging, 8 bits/sample.

- Survey speed[4]: FoV x $(A/T)^2$ x BW $= 3 \times 10^{17}$ $\rm deg^2\ m^4\ K^{-2}\ Hz^{-1}$ at 1.5 GHz; FoV x $(A/T)^2$ x BW $= 1.5 \times 10^{19}$ $\rm deg^2\ m^4\ K^{-2}\ Hz^{-1}$ at 0.7 GHz

- Antenna pointing and slewing: Blind pointing < 0.1 HPBW, move between adjacent sky positions separated by 0.5 HPBW in 3 sec, move between sky positions sep. by 90 deg. in < 60 s

- Instrumental polarization: Polarization error / total intensity -40 dB at FoV center, -30 dB out to FoV edge (after routine calibration)

- Spectral dynamic range: $10^4$ (flatness of bandpass response after calibration)

- Total power calibration: Total power (zero-spacing) flux density measured with 5% error within 1 hr.

Table 3
SKA rms sensitivity in 1 hour

| Frequency GHz | Bandwidth MHz | rms $\mu$Jy |
|---|---|---|
| 0.2 | 50 | 1.4 |
| 1.4 | 350 | 0.13 |
| 8 | 2000 | 0.06 |
| 20 | 4000 | 0.08 |

For calculations concerning cosmologically distant sources, a standard 'concordance cosmology' was adopted with $H_0 \simeq 70\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$, $\Omega_M \simeq 0.3$, $\Omega_\Lambda \simeq 0.7$, and $\Omega_B \simeq 0.04$ (and $\sigma_8 \simeq 1$ and $n_{\rm scalar} \simeq 1$ for the normalisation and shape of the matter power spectrum) unless stated otherwise.

We were unable (or perhaps unwilling) to enforce uniformity over important trivia like systems of units, sign conventions (e.g. on radio spectral index $\alpha$) and American versus the Queen's English.

## 4. Acknowledgements

The editors would like to thank the members of the ISAC, and in particular, the chairs of the working groups, for their efforts in writing the SKA science case. This was truly a team effort, and would never have been completed without substantial organizational and scientific input from the working groups.

Likewise, we thank the authors for their contributions. It is clear from reading the articles that the authors took seriously the charge to present substantive, original, and relevant research programs that can be accomplished with the SKA. We encourage all to continue these exciting lines of research.

We thank the ISSC, and in particular the two ISSC chairs, Ron Ekers and Jill Tarter, for their support (and protection!) during the time this work was undertaken. And lastly, we thank the project director, Richard Schilizzi, for guidance and leadership throughout the process.

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[4]Survey speed here means the speed with which a fixed sky area is surveyed to a fixed limiting flux density.